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## Spin-transfer Induced Switching in Magnetic Nanopillars

Jonathan Z. Sun

Lake Geneva, August 31th, 2004      8/23/2004      © 2004 IBM Corporation

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### Outline

- What is a spin-torque.
- Spin-torque experiments:
  - Sample fabrication
  - Quasi-static transport measurements.
  - High-speed switching.
  - Observation of microwave emission.
- Spin-torque: basic physics.
  - Angular momentum flow, spin-angular momentum conservation.
  - Current flow, spin transport, inverse effect of GMR/TMR.
  - Entropy flow: finite temperature effects in nanomagnets with spin-torque.
  - Energy flow: threshold voltage, threshold current, and their relationships.
- Spin-torque applications:
  - Current-driven switching of a nanomagnet -- MRAM beyond 30nm.
  - Current-tunable microwave generation in nano-junctions.
  - Current-amplified magnetic noise in GMR read-heads.
- Summary.

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### Spin-angular momentum flow: a basic picture

- Angular momentum exchange between a spin-current and a ferromagnet (FM).
- Precession and reversal of FM moment. J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996); ibid, 195, L261 (1999).

J. Z. Sun, J. Magn. Magn. Mater. 202, 157 (1999); Nature 425, 359 (2003).

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### Subtractive process, an example:

- The layout:

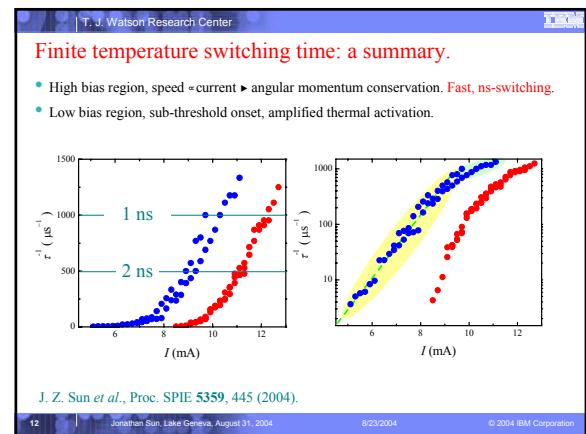
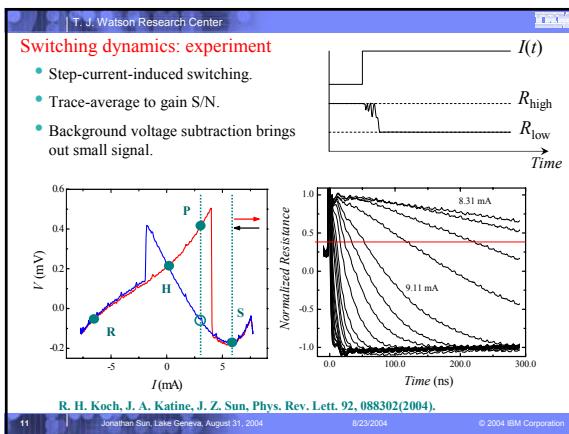
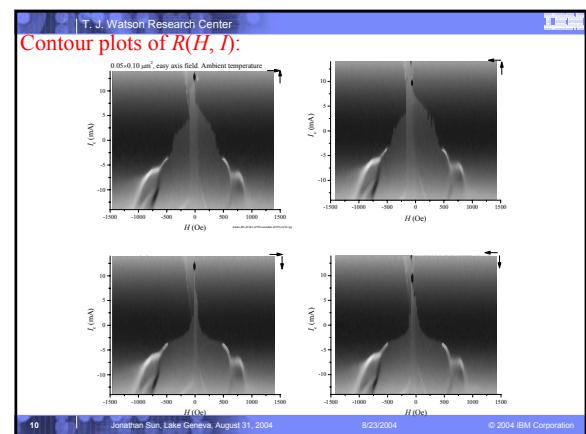
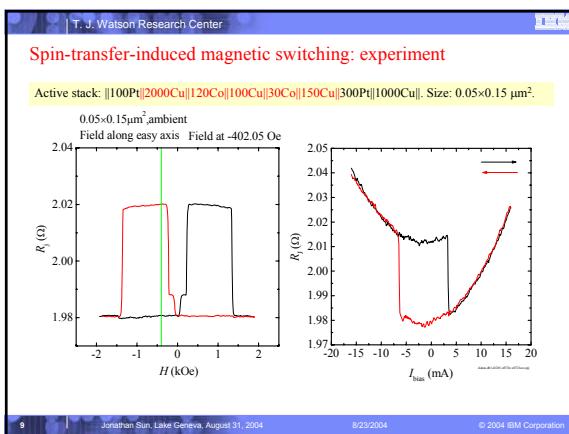
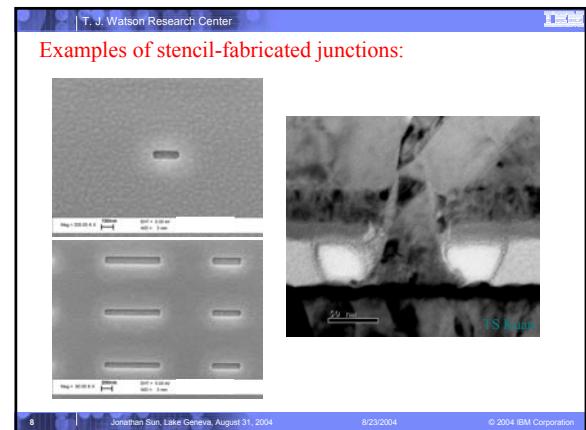
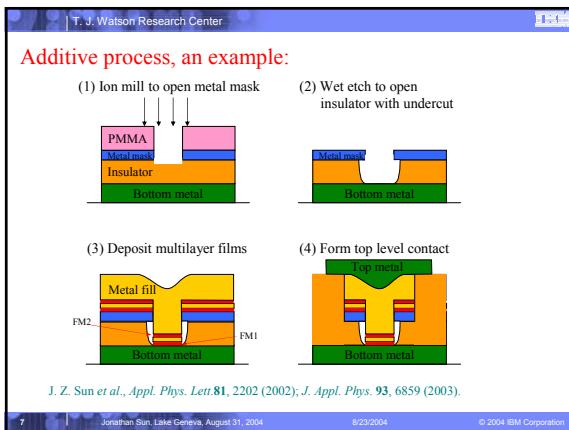
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### Subtractive process, an example:

J. Z. Sun, Lu Chen, Y. Suzuki, S. S. P. Parkin, R. H. Koch, J. Magn. Magn. Mater. 247, L237 (2002).

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### Single-domain magnetic dynamics, with spin-transfer

- Spin-transfer-induced torque:
 
$$\Gamma = -\left(\frac{\hbar}{2e}\right)\frac{\eta I}{m^2}(\mathbf{n}_s \times \mathbf{m}) \times \mathbf{m}$$
- Landau-Lifshitz-Gilbert Equation:
 
$$\left(\frac{1}{\gamma}\right)\frac{d\mathbf{m}}{dt} = \mathbf{m} \times \left[ \mathbf{H} - \left(\frac{\alpha}{m}\right)\mathbf{m} \times \left( \mathbf{H} + \frac{\eta\hbar}{2em\alpha} I \mathbf{n}_s \right) \right]$$

$$\text{If } \mathbf{H} \text{ and } \mathbf{H}_s \text{ collinear: } \left( H + \frac{\eta\hbar}{2em\alpha} I \right) \mathbf{n}_s = \left( 1 + \frac{H_s}{H} \right) \mathbf{H}$$

$$\left(\frac{1}{\gamma}\right)\frac{d\mathbf{m}}{dt} = \mathbf{m} \times \left[ \mathbf{H} - \left(\frac{\alpha}{m}\right)\left(1 + \frac{H_s}{H}\right) \mathbf{m} \times \mathbf{H} \right] = \mathbf{m} \times \left[ \mathbf{H} - \left(\frac{\tilde{\alpha}}{m}\right) \mathbf{m} \times \mathbf{H} \right]$$
- Threshold for precession amplification:
 
$$\tilde{\alpha} = \left(1 + \frac{H_s}{H}\right)\alpha \leq 0$$

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### Single-domain magnetic dynamics, with spin-transfer

J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999). J. Z. Sun, Phys. Rev. B**62**, 570 (2000)

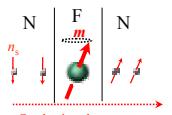
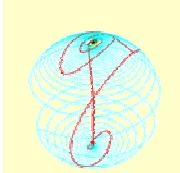
- Threshold for amplification:
 
$$\tilde{\alpha} = \left(1 - \frac{I}{I_c}\right)\alpha \leq 0$$

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### Spin transfer induced switching: a threshold current $I_c$ :

J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999). J. Z. Sun, Phys. Rev. B**62**, 570 (2000)

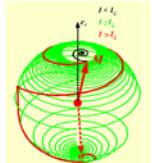
- Threshold for amplification:
 
$$\tilde{\alpha} = \left(1 - \frac{I}{I_c}\right)\alpha \leq 0$$
- 
- $$I_c(H) = \left(\frac{2e}{\hbar}\right)\left(\frac{\alpha}{\eta}\right)m(H_k + 2\pi M_s + H)$$
- Switching current threshold  $\propto H_{\text{total}}$ :
  - Slope  $\approx \alpha$
  - Intercept / slope  $\gg H_k + 2\pi M_s$
- 

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### Spin-angular momentum flow and conservation:

- Reversal speed proportional to current:
 
$$\tau^{-1} = \left(\frac{\eta\mu_B}{me}\right) \frac{1}{\ln(\pi/2\theta_0)} (I - I_{c0})$$

$$(I > I_{c0}) \quad (\text{for zero temperature})$$
- 
- Finite temperature: thermalized initial angle:
 
$$\langle \tau \rangle^{-1} \approx \left(\frac{\eta\mu_B}{me}\right) \left[ \frac{\ln(4\pi h_p)}{\pi \ln\left(\frac{K}{k_B T}\right)} \sqrt{\frac{1+h}{h_p}} \right] \times (I - I_{c0})$$

$$\begin{cases} h = H/H_k \\ h_p = H_p/H_k = 4\pi M_s/H_k \end{cases}$$

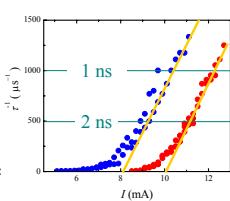
R. H. Koch et al., Phys. Rev. Lett. **92**, 088302 (2004); J. Z. Sun et al., Proc. SPIE **5359**, 445 (2004).

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R. H. Koch et al., Phys. Rev. Lett. **92**, 088302 (2004); J. Z. Sun et al., Proc. SPIE **5359**, 445 (2004).

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### Finite temperature switching time: a summary.

$$\left\{ \begin{array}{l} \langle \tau \rangle^{-1} \approx \left(\frac{\eta\mu_B}{me}\right) \left[ \frac{\ln(4\pi h_p)}{\pi \ln\left(\frac{K}{k_B T}\right)} \sqrt{\frac{1+h}{h_p}} \right] \times (I - I_{c0}), \quad (I \gg I_{c0}) \\ \tau^{-1} = \tau_0^{-1} \exp\left[-\frac{E_0}{k_B T} \left(1 - \frac{H}{H_k}\right)^2 \left(1 - \frac{I}{I_{c0}}\right)\right], \quad (I \ll I_{c0}) \end{array} \right.$$

- High bias region, speed «current ▶ angular momentum conservation. Fast, ns-switching.
- Low bias region, sub-threshold onset, amplified thermal activation.

Caution: (1) Mono-domain model only. Continuous medium more complex.  
 (2) Does not apply when  $I \sim I_{c0}$ .  
 (3) Does not apply when  $E_0(1-H/H_k)^2/k_B T \sim 1$ .

J. Z. Sun et al., Proc. SPIE **5359**, 445 (2004).

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### Single-domain dynamics, spin-transfer at finite temperature

- Landau-Lifshitz-Gilbert Equation at finite T:**

W. F. Brown, Jr. Phys. Rev. **130**, 1677 (1963):

$$H_{L,i} = \sqrt{2\alpha k_B T / \gamma m} I_{run,i}(t) \quad (i = x, y, z)$$

$$\frac{1}{\gamma} \frac{d\mathbf{m}}{dt} = \mathbf{m} \times \left[ (\mathbf{H} + \mathbf{H}_L) - \left( \frac{\alpha}{m} \right) \mathbf{m} \times \left( \mathbf{H} + \frac{\eta \hbar}{2em\alpha} \mathbf{I} \mathbf{n}_s \right) \right]$$

If  $\mathbf{H}$  and  $\mathbf{H}_s$  collinear:  $\left( H + \frac{\eta \hbar}{2em\alpha} I \right) \mathbf{n}_s = \left( 1 + \frac{H_s}{H} \right) \mathbf{H}$

$$\frac{1}{\gamma} \frac{d\mathbf{m}}{dt} = \mathbf{m} \times \left[ (\mathbf{H} + \mathbf{H}_L) - \left( \frac{\tilde{\alpha}}{m} \right) \mathbf{m} \times \mathbf{H} \right] \quad \tilde{\alpha} = \left( 1 + \frac{H_s}{H} \right) \alpha$$

$$H_{L,i} = \sqrt{2\tilde{\alpha}k_B \tilde{T} / \gamma m} I_{run,i}(t) \quad (i = x, y, z) \quad \alpha T = \tilde{\alpha} \tilde{T}$$

- Effective macrospin temperature is**

$$\tilde{T} = (\alpha / \tilde{\alpha}) T = T / (1 + H_s / H)$$

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### Finite temperature spin-transfer dynamics, cont.

- Effective magnetic temperature is**

$$\tilde{T} = (\alpha / \tilde{\alpha}) T = T / (1 + H_s / H) = T / (1 - I / I_{c0})$$

$$\left( \frac{1}{\gamma} \frac{d\mathbf{m}}{dt} = \mathbf{m} \times \left[ (\mathbf{H} + \mathbf{H}_L) - \left( \frac{\tilde{\alpha}}{m} \right) \mathbf{m} \times \mathbf{H} \right] \right) \quad \tilde{\alpha} = \left( 1 + \frac{H_s}{H} \right) \alpha$$

- Sub-threshold behavior, thermal activation:**

life-time

$$\tau = \tau_0 \exp \left[ \frac{E_0}{k_B T} \left( 1 - \frac{H}{H_k} \right)^2 \left( 1 - \frac{I}{I_{c0}} \right) \right]$$

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### Finite temperature theory of Li and Zhang:

Z. Li and S. Zhang, Phys Rev. B **69**, 134416 (2004). (zhangshu@missouri.edu)

$$\left\{ \begin{array}{l} \frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times (\mathbf{H}_{eff} + \mathbf{h}_r) - \frac{\alpha}{M_s} \mathbf{M} \times [\mathbf{M} \times (\mathbf{H}_{eff} + \mathbf{h}_r)] + \Gamma_s \\ \frac{\partial P}{\partial t} + \nabla_M \cdot \mathbf{J} - \lambda \nabla_M^2 P = 0 \end{array} \right. \text{where } P = P(\mathbf{M}, t), \text{ and } \mathbf{J} = P \frac{d\mathbf{M}}{dt}$$

Rate equation: angular momentum conservation. Probability density for  $(\mathbf{M}, t)$ . Probability current density for  $(\mathbf{M}, t)$ .

- Stationary solution:**  $\frac{\partial P_s}{\partial t} = 0$
- Trial solution:**  $P_s \propto \exp \left( -\frac{E}{k_B T^*} \right)$
- Lowest order:**  $T^* = T \left( 1 - \frac{a_J}{a_c} \right)^{-1} \quad \frac{E}{k_B T} \gg 1$

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### Spin-current switch for magnetic memory:

- Current rather than field driven switch of  $\mathbf{M}$ :** => Local addressing without proximity disturbance
- Threshold current  $I_c$ :** Easy-plane shape anisotropy and applied field

$$I_c = \frac{1}{\eta} \left( \frac{2e}{h} \right) \alpha \left( a^2 I_m H_k M_s \right) \left[ 1 + \left( 2\pi M_s + H_a \right) / H_k \right]$$

Uniaxial anisotropy energy of the cluster:  $\leftrightarrow$  Blocking temperature  $T_b$ . LLG damping coefficient.

Spin-polarization

- Quantitative estimates:**

For a cobalt cluster with  $T_b=600$  K,  $\eta \sim 0.1-0.5$ ,  $\alpha = 0.01$  with no easy-plane shape anisotropy and in zero applied field:  $I_c \sim 10$  to  $100 \mu\text{A}$ .

J. Z. Sun, Phys. Rev. B **62**, 570 (2000), US Patent 6,130,814; 6,256,223.  
J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996); ibid., **195**, L261 (1999). US Patent 5,695,864.

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### Summary

- Spin-transfer: a new mechanism of current-magnetic moment interaction.
- Spin-transfer can switch hard nano-magnets of  $H_k \sim 1$  Tesla without large field.
- Spin-transfer switching is fast: sub-nanosecond switching demonstrated.
- A new mechanism for localized high-torque magnetic writing.
- For CMOS integration, need:
  - 10 - 100X larger junction resistance ( $\sim 1\text{k}\Omega$ ), for read-out  $\Delta V >$ , say, 10mV.
  - At least 10X reduction in junction switching current ( $< 0.1$  mA).

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**Acknowledgement**

IBM	Roger Koch Mike Rooks Jim Harper Stephen Rossnagel Roy Carruthers John Sloneczewski David Abraham Philip Trouilloud Maxim Tsoi Stuart Parkin	Andy Kent Barbaros Oeztaylmez Wenyu Chen	NYU
	T. S. Kuan	SUNY Albany	
	Arne Brataas	NUST	

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